

# Diboson Production and Couplings

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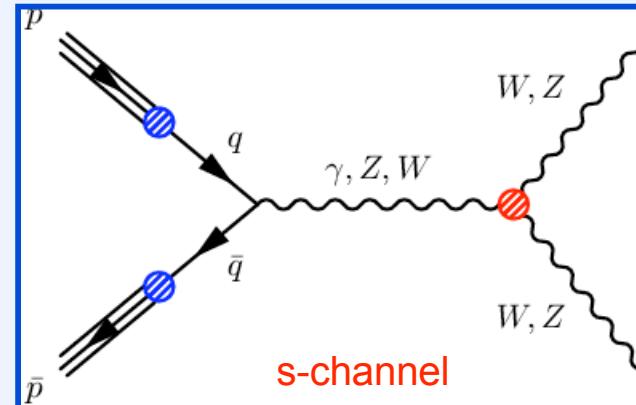
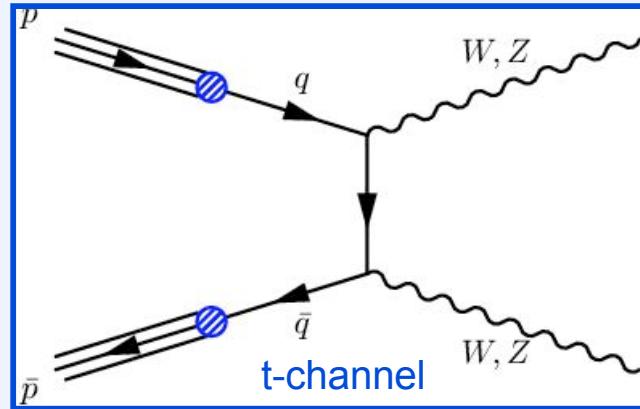
on behalf of the D0 and  
CDF Collaborations

July 30, 2008



# Why Study Diboson Production?

## Leading order diagrams



- s-channel production probes non-Abelian structure of  $SU(2)_L \otimes U(1)_Y$
- Tevatron ( $p\bar{p}$ ) sensitive to different Triple Gauge Couplings(TGCs) than LEP ( $e^+e^-$ ) and explores higher  $\hat{s}$

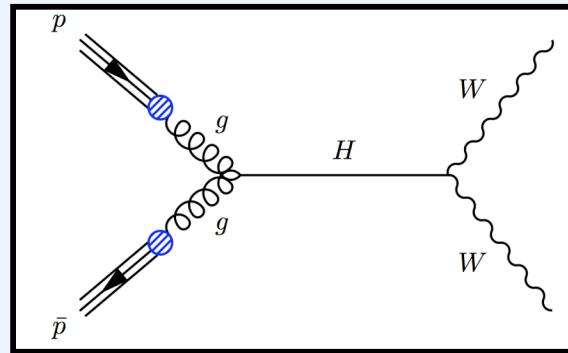
$$\begin{aligned}
 q\bar{q}' &\rightarrow W^{(*)} \rightarrow W\gamma : WW\gamma \\
 q\bar{q}' &\rightarrow W^{(*)} \rightarrow WZ : WWZ \\
 q\bar{q} &\rightarrow Z/\gamma^{(*)} \rightarrow WW : WW\gamma, WWZ \\
 q\bar{q} &\rightarrow Z/\gamma^{(*)} \rightarrow Z\gamma : ZZ\gamma, Z\gamma\gamma \\
 q\bar{q} &\rightarrow Z/\gamma^{(*)} \rightarrow ZZ : ZZ\gamma, ZZZ
 \end{aligned}$$

Not permitted in SM

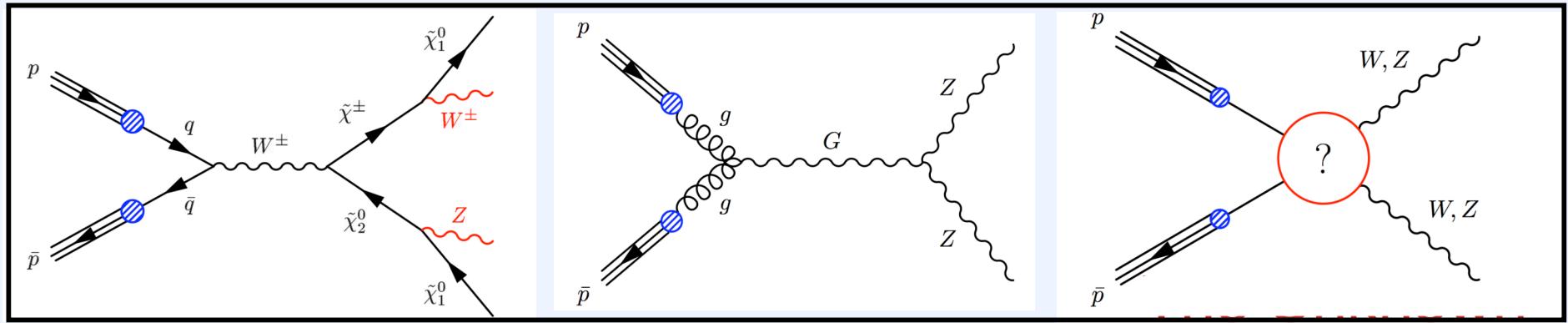
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# Why Study Diboson Production?

- Important background for Higgs Searches!



- New physics could appear as enhanced rate of diboson production!



SUSY

Randall-Sundrum Graviton

Unknown



# Diboson Production at the Tevatron

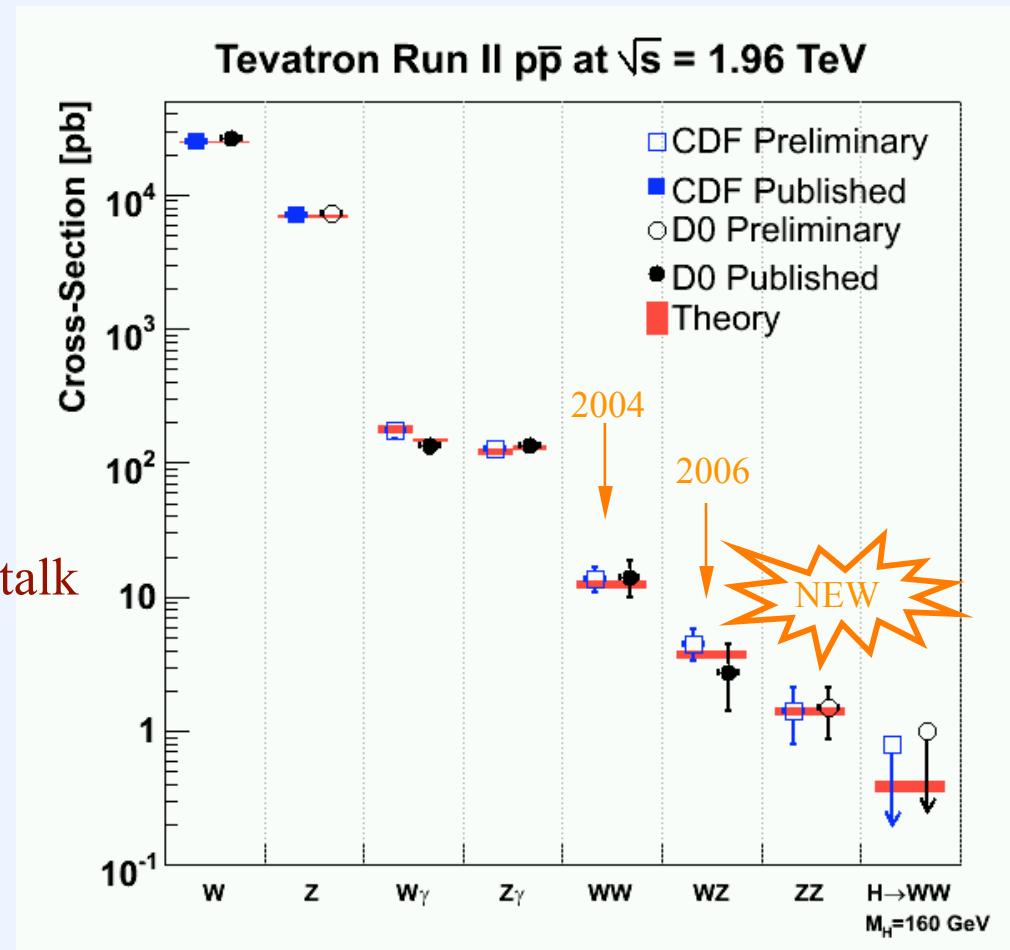


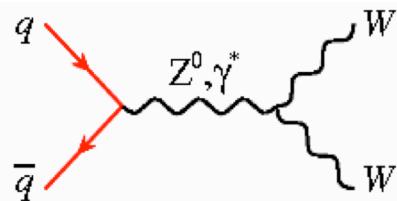
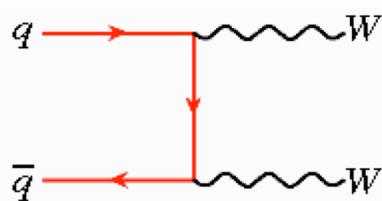
- Analyses presented:  $\sim 1\text{--}2.7 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s}=1.96 \text{ TeV}$

Channel	Events/ $\text{fb}^{-1}$
$W \rightarrow l\nu$	$\approx 5,000,000$
$Z \rightarrow ll$	$\approx 500,000$
$W\gamma \rightarrow l\nu\gamma$	$\approx 32,000$
$Z\gamma \rightarrow ll\gamma$	$\approx 8000$
$WW/WZ \rightarrow lljj$	$\approx 4000$
$WW \rightarrow llvv$	$\approx 600$
$WZ \rightarrow llvv$	$\approx 50$
$ZZ \rightarrow llvv$	$\approx 40$
$ZZ \rightarrow llll$	$\approx 6$

$l=e \text{ or } \mu$

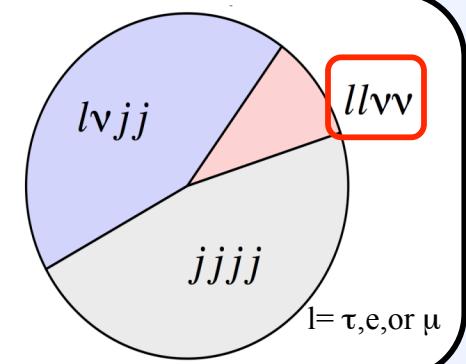
} in this talk





NLO cross section:  $12.4 \pm 0.8 \text{ pb}$   
 Campbell, Ellis, Phys.Rev. D60 (1999) 113006

- Small BR:  $\sim 5\text{-}6\%$  ( $l = e \text{ or } \mu$ )
- Include  $W \rightarrow \tau\nu$ ,  $\tau \rightarrow l\nu\nu$
- Clean sample



- Important quasi-irreducible background for  $H \rightarrow WW$
- Probes  $WW\gamma$  and  $WWZ$  trilinear gauge couplings
- D0  $\sim 250 \text{ pb}^{-1}$  (PRL 94 151801) *First Tevatron observation (5.2 $\sigma$ )*
  - 25 candidates, expected background  $8.1 \pm 1.0$  events

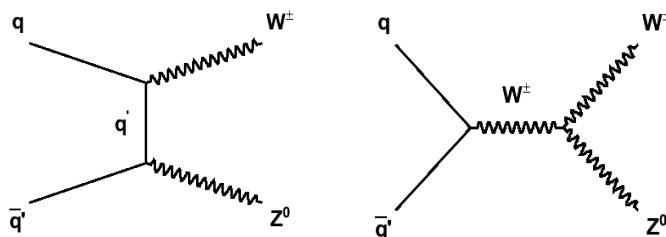
$$\sigma(WW) = 13.8^{+4.3}_{-3.8}(\text{stat})^{+1.2}_{-0.9}(\text{syst}) \pm 0.9(\text{lum}) \text{ pb}$$

- CDF  $\sim 825 \text{ pb}^{-1}$ 
  - 95 candidates,  $37.8 \pm 4.8$  expected background events

$$\sigma(WW) = 13.6 \pm 2.3(\text{stat}) \pm 1.6(\text{syst}) \pm 1.2(\text{lum}) \text{ pb}$$

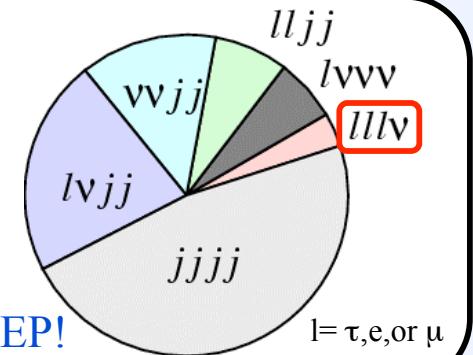


# WZ → lνll @ D0



NLO cross section:  $3.7 \pm 0.3$  pb  
 Campbell, Ellis, Phys. Rev. D60 (1999) 113006

- Small BR: ~2% ( $l = e$  or  $\mu$ )
- Include  $W \rightarrow \tau\nu$ ,  $\tau \rightarrow l\nu\nu$
- Clean sample
- WZ not produced at LEP!



## D0 @ 1 fb<sup>-1</sup>

3 isolated leptons, e or  $\mu$

$P_T > 15$  GeV

$71 < M_{ee} < 111$  GeV

$50 < M_{\mu\mu} < 130$  GeV

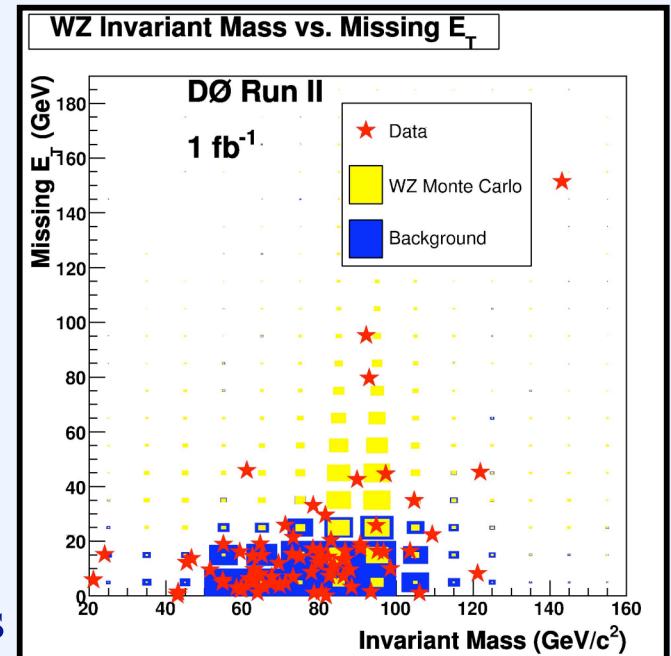
MET  $> 20$  GeV

Transverse recoil (WZ)  $< 50$  GeV

- 13 candidates, expected background  $4.5 \pm 0.6$  events

$$\sigma(WZ) = 2.7^{+1.7}_{-1.3} (stat + syst) pb$$

PRD 76 111104(R)





# WZ → lvll @ CDF



- Backgrounds: Z+jets (jet fakes lepton), Z $\gamma$  ( $\gamma$  fakes lepton), ZZ (unidentified lepton), t $\bar{t}$

CDF @ 1.9 fb $^{-1}$

3 isolated leptons, e or  $\mu$

$P_T^1 > 20 \text{ GeV}, P_T^2 > 10 \text{ GeV}$

$76 < M_{ll} < 106 \text{ GeV}$

MET  $> 25 \text{ GeV}$

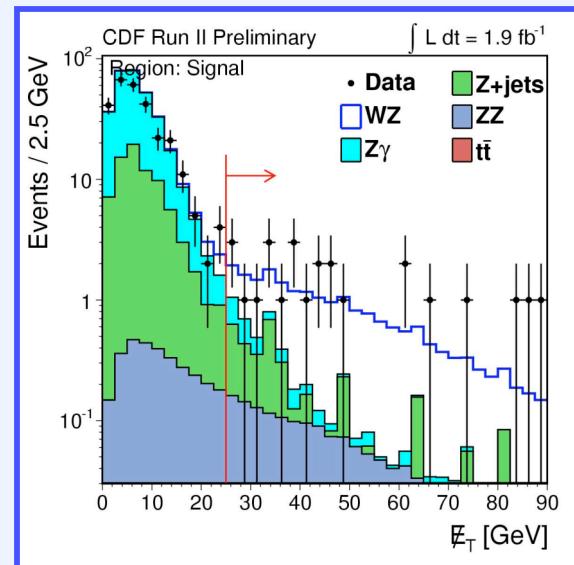
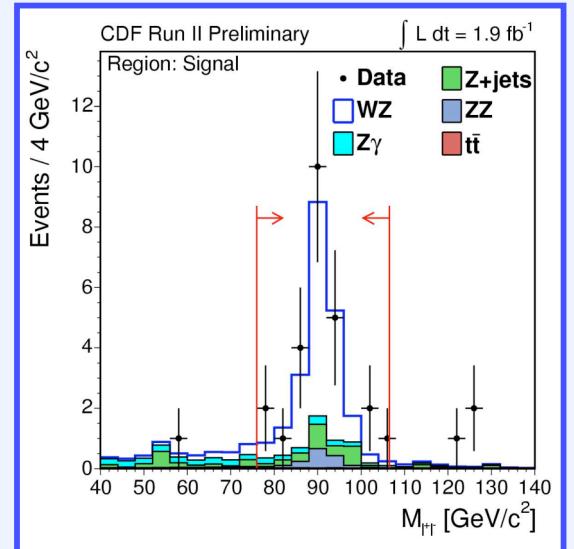
$\Delta\phi(\text{MET}, l \text{ or } j) > 9^\circ$

$\leq 1 \text{ jet}, P_T > 15 \text{ GeV}$

if 2nd dilepton pair, veto  $P_T > 8 \text{ GeV}$  track

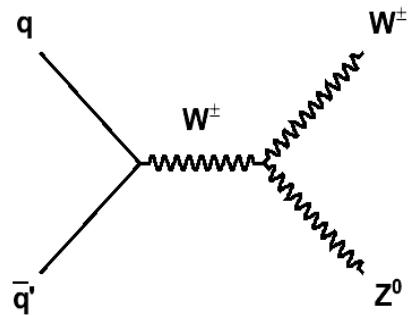
- 25 candidates, expected background  $4.7 \pm 0.8$  events

$$\sigma(WZ) = 4.4^{+1.3}_{-1.0} (\text{stat}) \pm 0.2 (\text{syst}) \pm 0.3 (\text{lum}) \text{ pb}$$





# WWZ Anomalous Couplings



- WZ not produced at LEP
- Tevatron can set limits on WWZ production independent of WWγ production
- Write effective Lagrangian in terms of CP-conserving vector boson (V) coupling parameters ( $g_1$ ,  $\kappa$ , and  $\lambda$ ):

$$L_{WWV}/g_{WWV} = i\mathbf{g}_1 \mathbf{V}(W^+_{\mu\nu} W^\mu V^\nu - W^+_{\mu} V_\nu W^{\mu\nu}) + i\kappa_V W^+_\mu W_\nu V^{\mu\nu} + i\lambda_V/M_W^2 W^+_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}$$

$$\text{SM: } g_1^\gamma = g_1^Z = 1$$

$$\text{SM: } \kappa_\gamma = \kappa_Z = 1$$

$$\text{SM: } \lambda_\gamma = \lambda_Z = 0$$

$$\text{AC: } \Delta g_1^Z (= g_1^Z - 1)$$

$$\text{AC: } \Delta \kappa_Z, \Delta \kappa_\gamma (= \kappa_V - 1)$$

$$\text{AC: } \lambda_Z, \lambda_\gamma$$

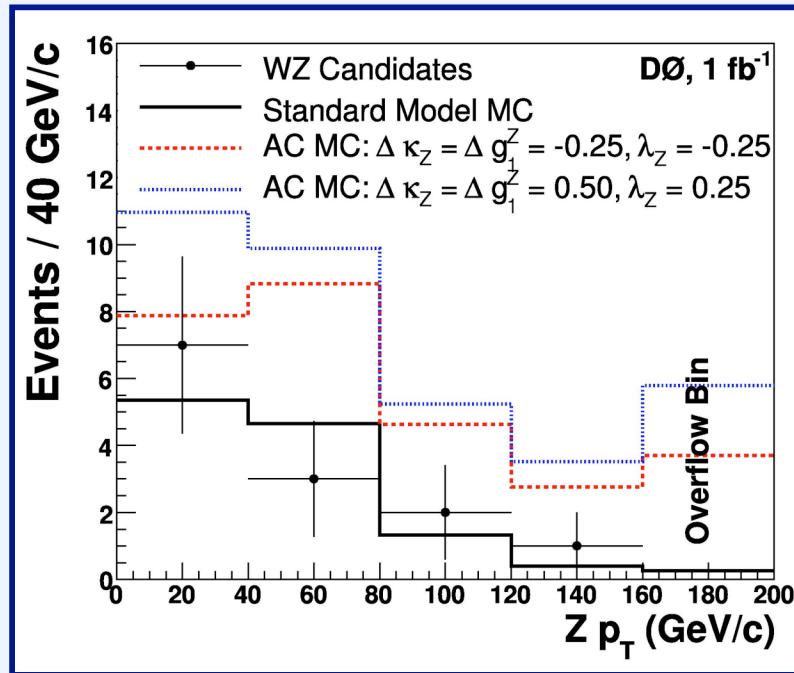
- Restrict coupling parameters to their Standard Model values at asymptotically high energies to maintain unitarity:

- form factor  $\Lambda$ , and  $\alpha = \Delta g_1, \Delta \kappa$ , or  $\lambda$

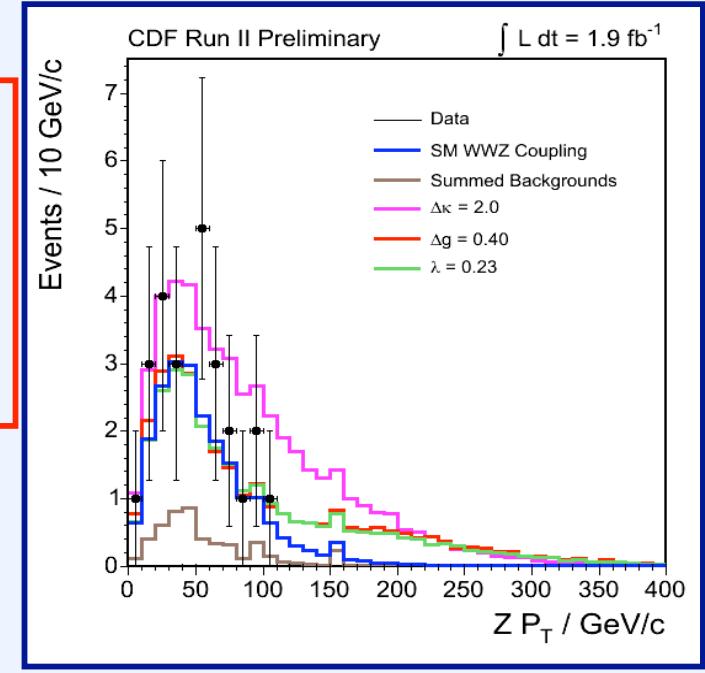
$$\alpha \rightarrow \frac{\alpha}{(1 + \hat{s}/\Lambda^2)^2}$$

# WWZ Anomalous Couplings

- $P_T(Z)$  sensitive to coupling parameters and easily measurable!

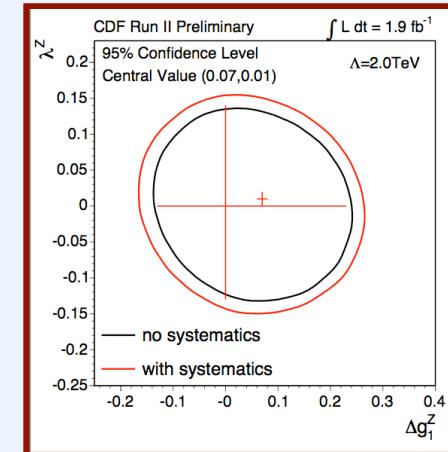


Perform 1-D and 2-D fits for  $\lambda, \Delta g, \Delta \kappa$  using WZ data candidates



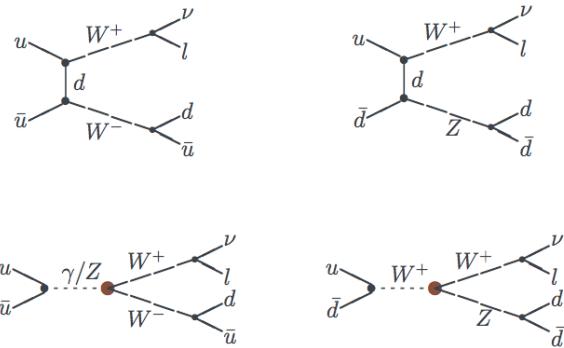
95% C.L. Limits, assuming  $\Lambda=2.0 \text{ TeV}$

D0 @ 1.0 $\text{fb}^{-1}$	CDF @ 1.9 $\text{fb}^{-1}$
$-0.17 < \lambda_Z < 0.21$	$-0.13 < \lambda_Z < 0.14$
$-0.14 < \Delta g_Z < 0.34$	$-0.13 < \Delta g_1^Z < 0.23$
$-0.12 < \Delta \kappa_Z = \Delta g_1^Z < 0.29$	$-0.76 < \Delta \kappa_Z < 1.18$





# WW/WZ → lvjj



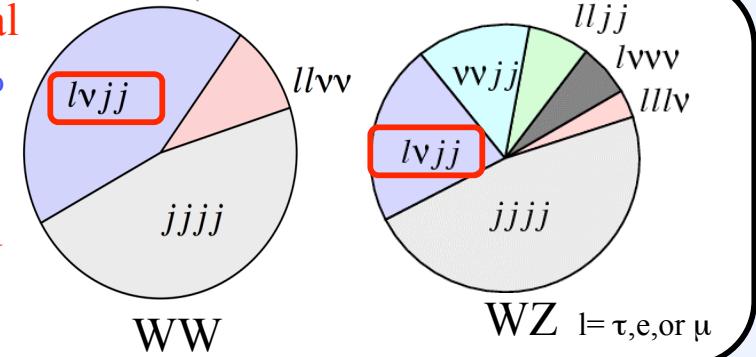
- 5-10× more signal

- Br(WW): 30%
- Br(WZ): 14%

$l = e \text{ or } \mu$

- 1000× more BKG

- S/B < 1%



- Final state similar to  $WH \rightarrow lvjj$
- Higher branching ratios = potentially greater sensitivity to anomalous TGCs
- Backgrounds: **W+jets**, Z+jets, QCD,  $t\bar{t}$

CDF @ 1.2  $\text{fb}^{-1}$

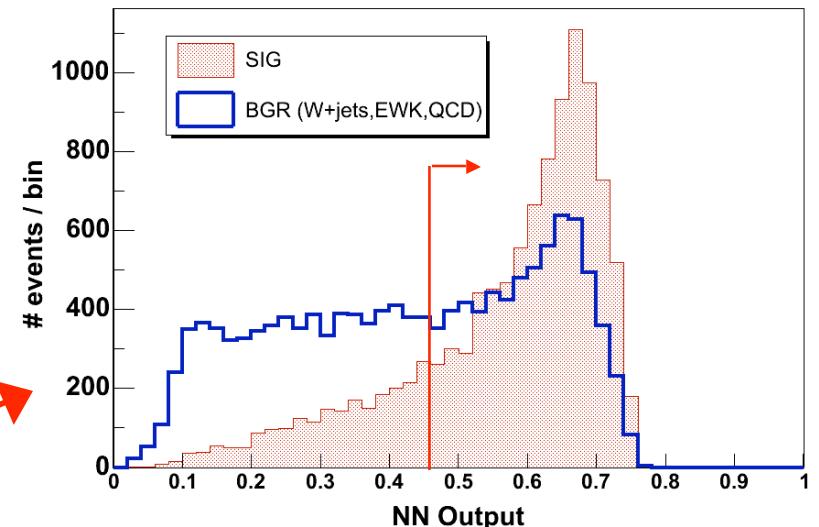
Exactly 1 lepton,  $e$  or  $\mu$

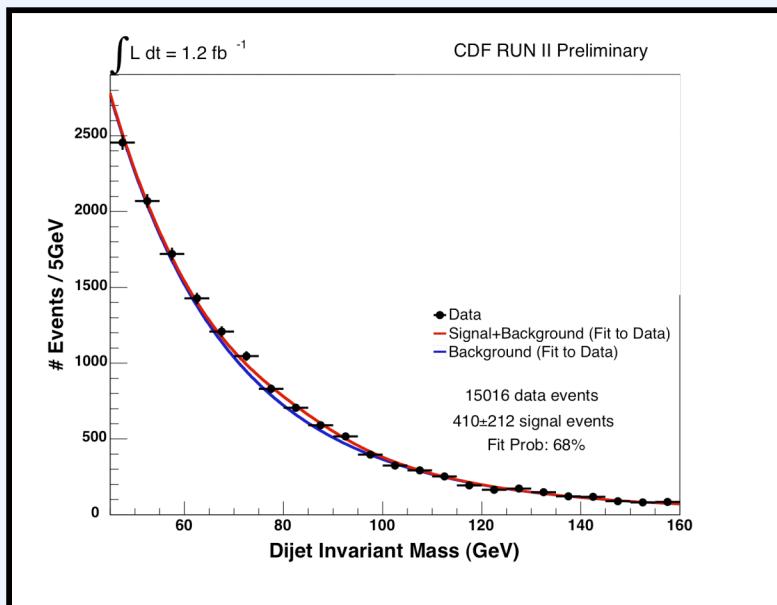
$\geq 2$  jets,  $P_T > 15 \text{ GeV}$ ,  $\Delta\eta(j_1, j_2) < 2.5$

MET  $> 25 \text{ GeV}$

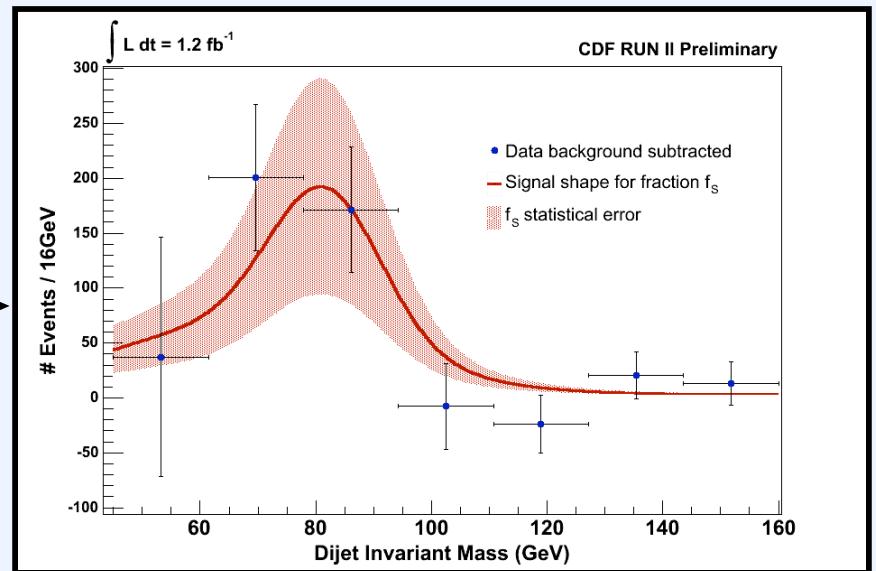
$30 \text{ GeV} < M_T(W) < 120 \text{ GeV}$

Neural Network: 6 dimensionless event shape variable inputs





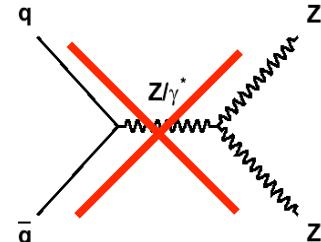
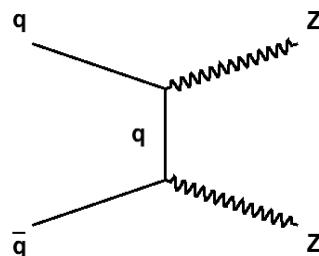
Subtract  
background  
shape from  
data



- Estimate signal fraction from likelihood fit to data for  $M_{jj}$ 
  - Signal shape fixed with Monte Carlo, background shape has 2 free parameters

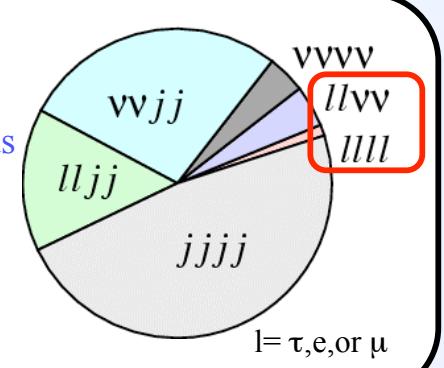
CDF 1.2 fb⁻¹	Signal yield	$410 \pm 212(\text{stat}) \pm 102(\text{syst})$
	Observed	$\sigma \times \text{Br} = 1.47 \pm 0.77(\text{stat}) \pm 0.38(\text{syst}) \text{ pb}$
	95% C.L. Limit	$\sigma \times \text{Br} < 2.88 \text{ pb}$
	NLO prediction	$\sigma \times \text{Br} = 2.09 \pm 0.14 \text{ pb}$

# ZZ Production



NLO cross section:  $1.4 \pm 0.1$  pb  
 Campbell, Ellis, Phys.Rev. D60 (1999) 113006

- llvv: ~3.0%
  - Large Backgrounds
  - llvv: ~0.5%
  - Clean Sample
- l=e or  $\mu$



- Demonstrates our ability to measure small cross sections
- ZZZ and ZZ $\gamma$  forbidden by SM  $\rightarrow$  opportunity to see new physics
- Both D0 and CDF consider decay modes: llvv and llll

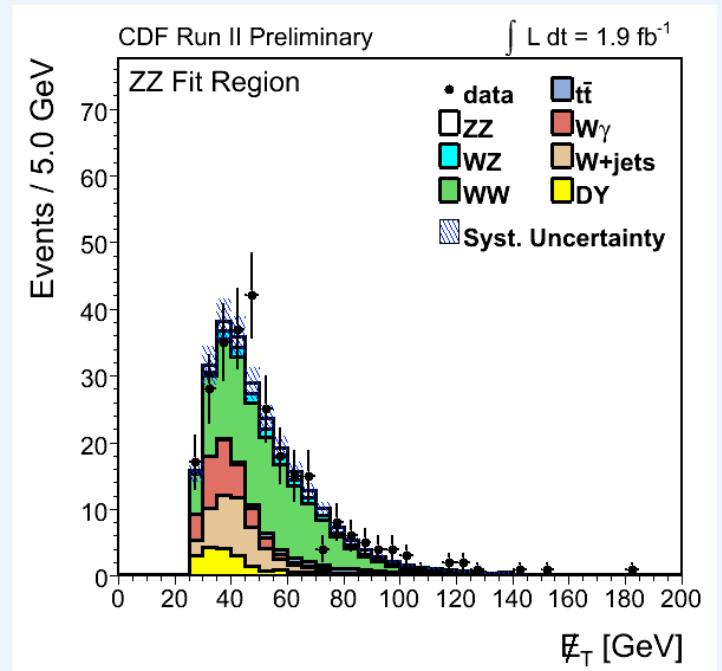


Results for production and couplings



- Backgrounds: Z/ $\gamma^*$ , WW, WZ, t $\bar{t}$ , W $\gamma$ , W+jets

CDF @ 1.9 fb $^{-1}$
Exactly 2 isolated, opposite sign leptons, e or $\mu$
$P_T^1 > 20 \text{ GeV}, P_T^2 > 10 \text{ GeV}$
$M_{ll} > 16 \text{ GeV}$
$\leq 1 \text{ jet}, P_T > 15 \text{ GeV}$
$E_{T,\text{sig}} > 2.5 \text{ GeV}^{1/2}, E_{T,\text{rel}} > 25 \text{ GeV}$

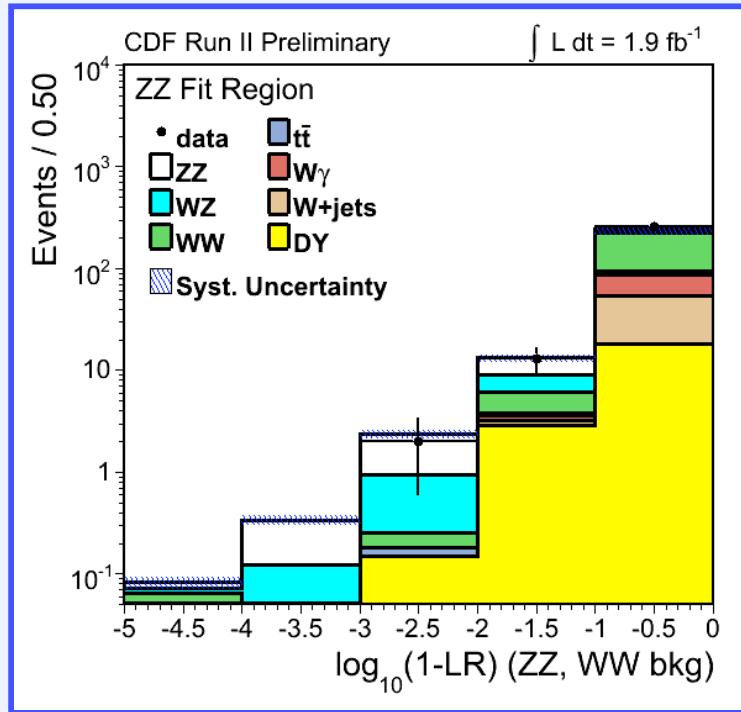


$$E_{T,\text{sig}} = \frac{E_T}{\sqrt{\sum E_T}}$$

$$E_{T,\text{rel}} \equiv \begin{cases} E_T & \text{if } \Delta\phi E_T, (l, \text{jet}) > \frac{\pi}{2} \\ E_T \sin \Delta\phi E_T, (l, \text{jet}) & \text{if } \Delta\phi E_T, (l, \text{jet}) < \frac{\pi}{2} \end{cases}$$

- Observe 276 events,  $256 \pm 21$  expected, including  $14 \pm 2$  expected signal events
- Dominant remaining background: WW (real missing- $E_T$ )

- Distinguish ZZ from WW with event-by-event probability density function:



$$LR = \frac{P_{ZZ}}{P_{ZZ} + P_{WW}}$$

Observed Results: CDF @ 1.9  $\text{fb}^{-1}$

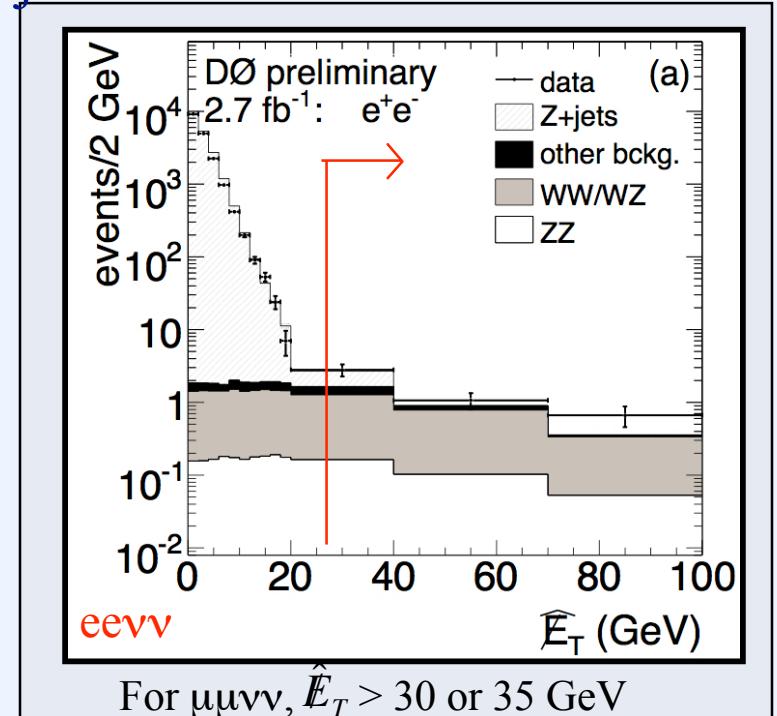
P-Value	0.12
Significance	$1.2\sigma$

- Probability for background-only hypothesis to describe data:
- Expected probability to see  $2\sigma(5\sigma)$  effect: 0.55(0.06)

- Backgrounds:  $Z+jets, WW, WZ, t\bar{t}, W\gamma, W+jets$

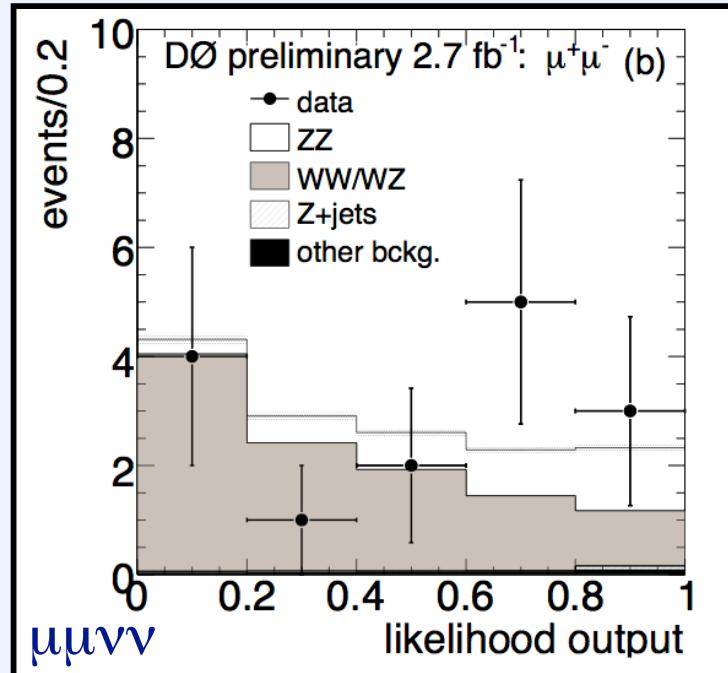
D0 @ 2.7 fb <sup>-1</sup>
Exactly 2 isolated, opposite sign leptons, e or $\mu$
$P_T > 15$ GeV
$70 < M_{ll} < 110$ GeV
$\leq 2$ jets, $P_T > 15$ GeV
Veto additional lepton candidates, $P_T > 5$ GeV

- To target  $Z+jets$  ( $\sim 13,000\times$  more than  $ZZ$ ), create novel missing- $E_T$  like object :
  - minimum possible missing- $E_T$  given uncertainties on lepton energies and hadronic recoil



Channel	eeVV	$\mu\mu VV$
Background	$15.6 \pm 0.4$	$10.9 \pm 0.3$
Total Predicted	$19.6 \pm 0.4$	$14.3 \pm 0.3$
Observed	28	15

- Distinguish ZZ from WW using multivariate likelihood:



- Probability for background-only to produce observed distribution:

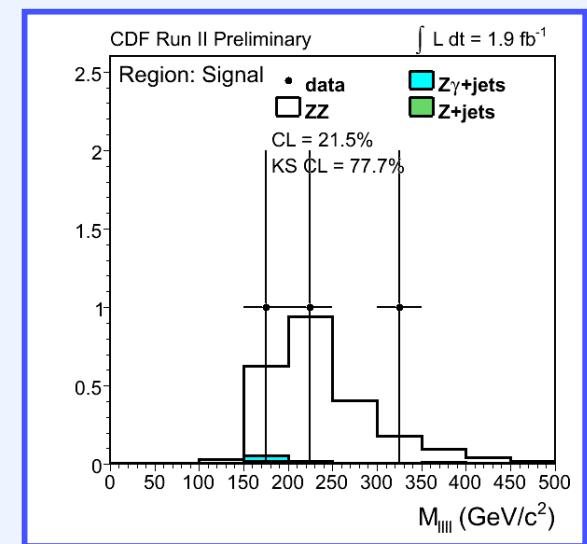
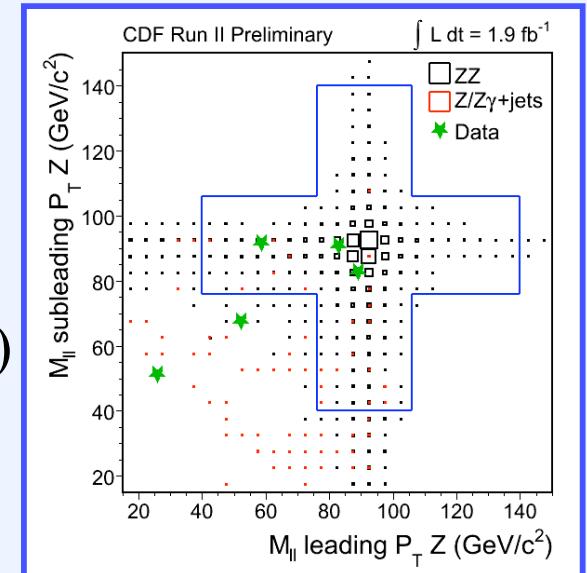


	Expected	Observed
P-value:	2.26x10 <sup>-2</sup>	0.40x10 <sup>-2</sup>
Significance:	2.00 $\sigma$	2.66 $\sigma$

- Dominant background: Z+jets (including  $Z\gamma$ +jets) with 2 fake leptons
- Require exactly isolated 4 leptons (e or  $\mu$ )
  - $P_T^1 > 20 \text{ GeV}$ ,  $P_T^{2,3,4} > 10 \text{ GeV}$
- Two Z candidates (opposite sign, same flavor pairs)
  - $76 < M_{ll}(Z_1) < 106 \text{ GeV}$
  - $40 < M_{ll}(Z_2) < 140 \text{ GeV}$
- Separate high and low purity samples:

Category	Candidates without a trackless electron	Candidates with a trackless electron
ZZ	$1.990 \pm 0.013 \pm 0.210$	$0.278 \pm 0.005 \pm 0.029$
$Z + \text{jets}$	$0.014^{+0.010}_{-0.007} \pm 0.003$	$0.082^{+0.089}_{-0.060} \pm 0.016$
Total	$2.004^{+0.016}_{-0.015} \pm 0.210$	$0.360^{+0.089}_{-0.060} \pm 0.033$
Observed	2	1

1 eeee and 2  $\mu\mu\mu\mu$  candidates

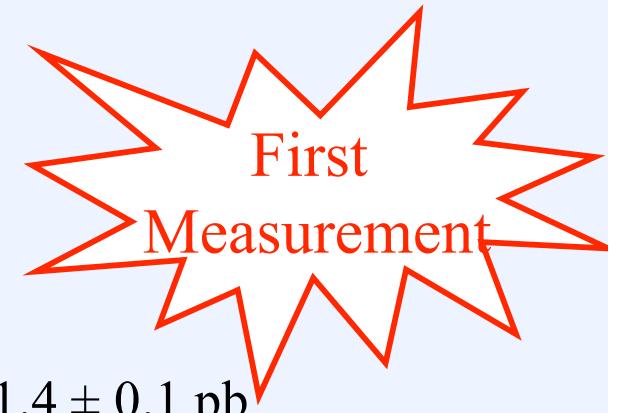


- Probability for data to be described by background-only hypothesis in ZZ $\rightarrow l\bar{l}vv$ , ZZ $\rightarrow l\bar{l}ll$ , and the combined channels:

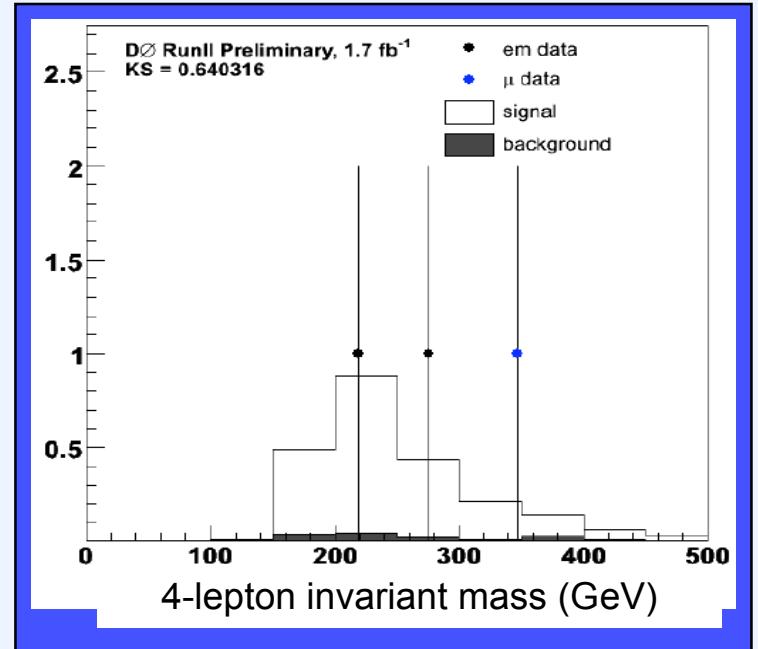
Observed Results: CDF @ 1.9 fb $^{-1}$			
Channel	l $\bar{l}vv$	l $\bar{l}ll$	Combined
P-value:	0.12	$1.1 \times 10^{-5}$	$5.1 \times 10^{-6}$
Significance:	$1.2\sigma$	$4.2\sigma$	$4.4\sigma$

PRL 100 2018 01

- Expected probability to observe a  $5\sigma$  effect is 0.50
- Cross section:  $\sigma(ZZ) = 1.4^{+0.7}_{-0.6} (stat + syst) pb$ 
  - Consistent with Standard Model NLO cross section:  $1.4 \pm 0.1$  pb



- Background: Z+jets (including Z $\gamma$ +jets), t $\bar{t}$
- Require exactly 4 leptons, e or  $\mu$ 
  - eeee/ $\mu\mu\mu\mu$ :  $P_T^1 > 30$ ,  $P_T^2 > 20$ ,  $P_T^{3,4} > 15$  GeV
  - ee $\mu\mu$ :  $P_T(e_1 \text{ or } \mu_1) > 20$ ,  $P_T(e_2 \text{ or } \mu_2) > 20$  GeV
- Two Z candidates (same flavor pairs)
  - $M_{ll}(Z_1) > 70$  GeV
  - $M_{ll}(Z_2) > 50$  GeV
- Separate higher and lower purity samples:
  - eeee or ee $\mu\mu$ : the more central (CC) electrons, which have a track match, the higher the purity



Lowest background channels!

Subchannel	eeee <sub>2CC</sub>	eeee <sub>3CC</sub>	eeee <sub>4CC</sub>	$\mu\mu\mu\mu$	ee $\mu\mu$ <sub>0CC</sub>	ee $\mu\mu$ <sub>1CC</sub>	ee $\mu\mu$ <sub>2CC</sub>
Luminosity (fb $^{-1}$ )	1.75 $\pm$ 0.11	1.75 $\pm$ 0.11	1.75 $\pm$ 0.11	1.68 $\pm$ 0.10	1.68 $\pm$ 0.10	1.68 $\pm$ 0.10	1.68 $\pm$ 0.10
Signal	0.094 $\pm$ 0.005	0.194 $\pm$ 0.006	0.158 $\pm$ 0.006	0.60 $\pm$ 0.05	0.065 $\pm$ 0.007	0.39 $\pm$ 0.04	0.62 $\pm$ 0.05
Z( $\gamma$ )+jets bkgd.	0.030 $^{+0.009}_{-0.008}$	0.018 $^{+0.008}_{-0.007}$	0.002 $^{+0.002}_{-0.001}$	0.0003 $^{+0.0001}_{-0.0001}$	0.03 $^{+0.02}_{-0.01}$	0.05 $\pm$ 0.01	0.008 $^{+0.004}_{-0.003}$
t $\bar{t}$ background	—	—	—	—	0.0012 $^{+0.0016}_{-0.0009}$	0.005 $\pm$ 0.002	0.0007 $^{+0.0009}_{-0.0005}$
Observed events	0	0	2	1	0	0	0

- Probability for data to be described by background-only hypothesis:

Observed Results: D0 @ 2.7 fb<sup>-1</sup>

Channel	llvv	llll (1.7 fb <sup>-1</sup> )	Combined*
P-value:	0.40x10 <sup>-2</sup>	4.33 x 10 <sup>-8</sup>	–
Significance:	2.7 $\sigma$ (2.0 $\sigma$ )	5.3 $\sigma$ (3.6 $\sigma$ )	5.7 $\sigma$ (5.2 $\sigma$ )



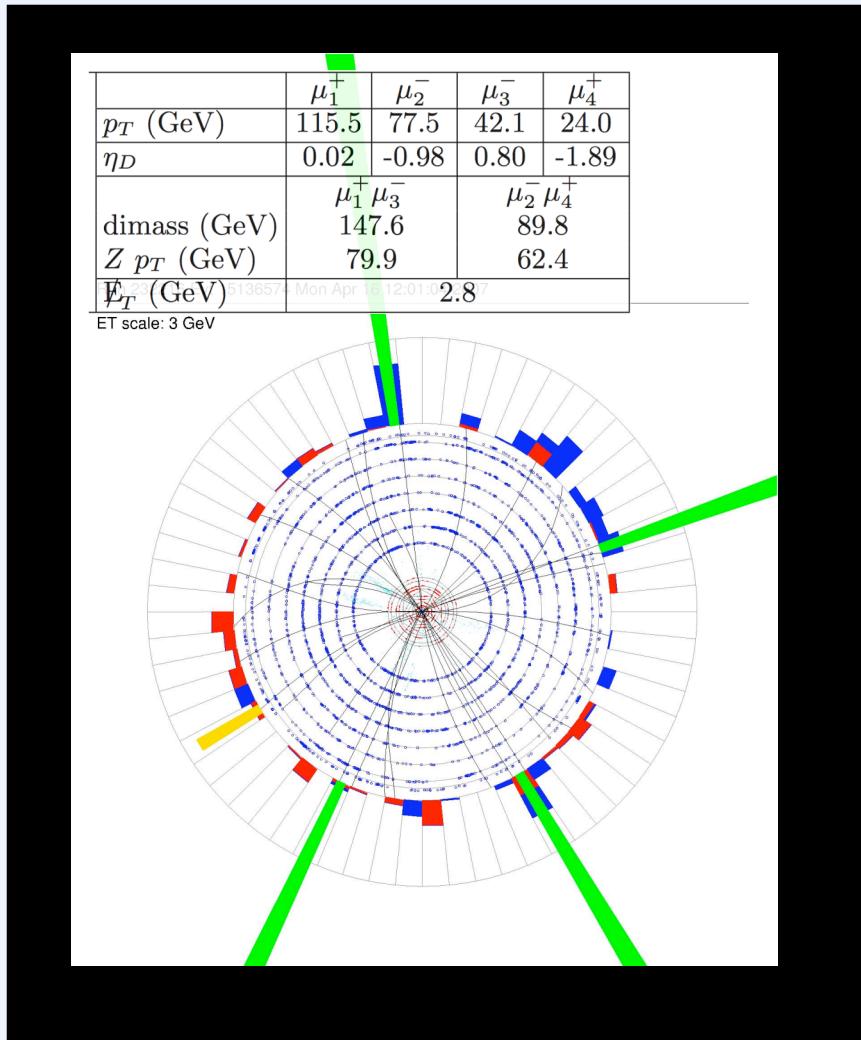
Expected significances are given in parentheses

- Combined result includes earlier 1fb<sup>-1</sup> search for ZZ → llvv (PRL 100 131801)
- Combined cross section:

$$\sigma(ZZ) = 1.48 \pm 0.59(stat)^{+0.17}_{-0.19} pb$$

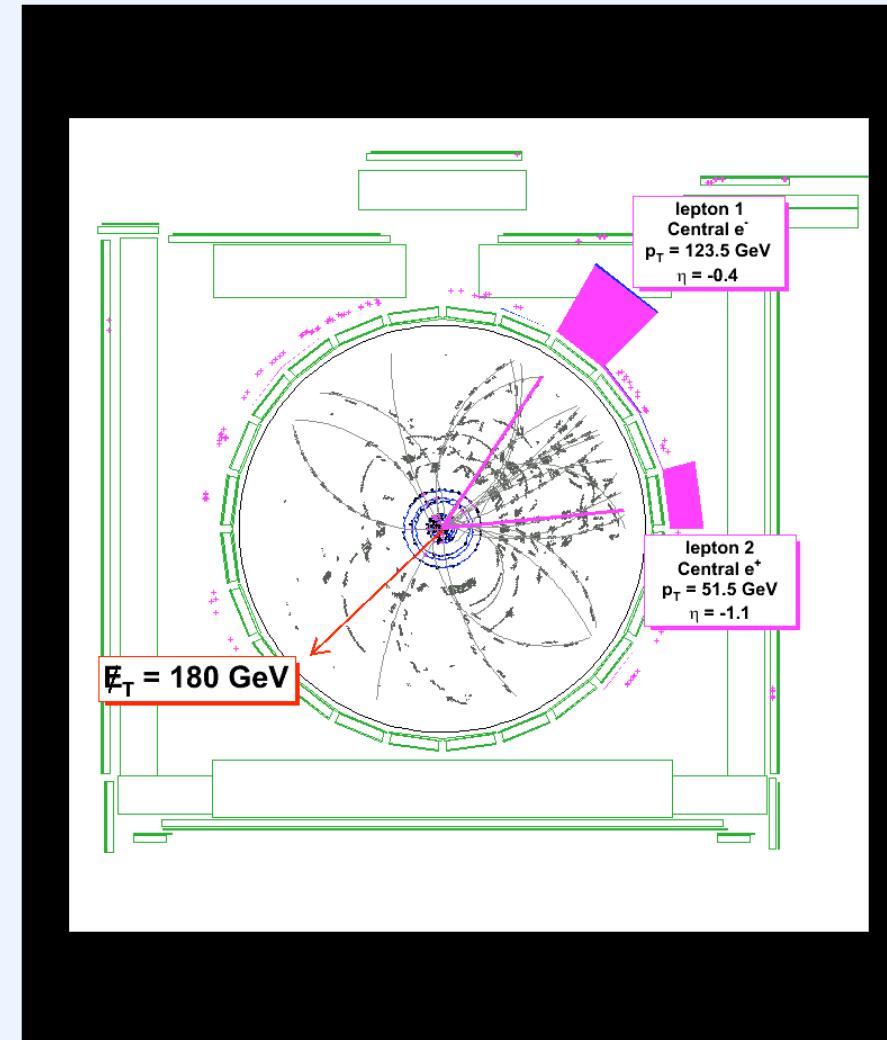
- Consistent with Standard Model NLO cross section: 1.4 ± 0.1 pb





D0:  $\mu\mu\mu\mu$  candidate

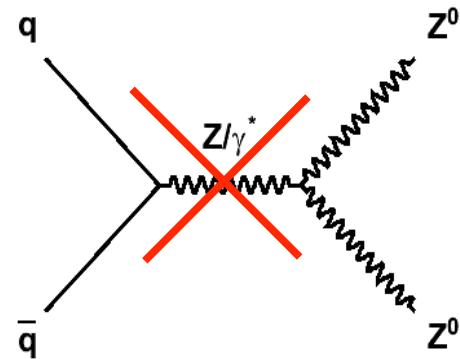
Susan Burke



CDF:  $e\bar{e}vv$  candidate

ICHEP 2008

# ZZZ/Z $Z\gamma$ Anomalous Couplings



- ZZZ and ZZ $\gamma$  production are not permitted in the SM
- Describe anomalous couplings in terms of CP-violating parameters  $f_4^Z$ ,  $f_4^\gamma$ , and CP-conserving parameters  $f_5^Z$ ,  $f_5^\gamma$
- Use form factor to ensure unitarity:

$$f_i^V \rightarrow \frac{f_i^V(\hat{s})}{(1 + \hat{s}/\Lambda^2)^3}$$

where  $V=Z,\gamma$

- D0 @ 1.1 fb $^{-1}$ : ZZ $\rightarrow llll$  channel

- Event selection similar to 1.7 fb $^{-1}$  analysis, except:  $M_{ll} > 50(70)$  GeV for ee( $\mu\mu$ ),  $P_T^l > 15$  GeV

1-D limits @ 95% C.L.

$\Lambda = 1.2$  TeV

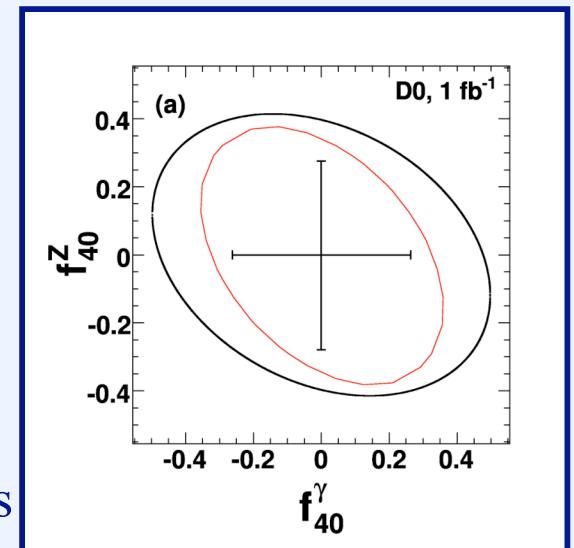
$-0.28 < f_4^Z < 0.28$
$-0.31 < f_5^Z < 0.29$
$-0.26 < f_4^\gamma < 0.26$
$-0.30 < f_5^\gamma < 0.28$

Example of 2-D limit  $\rightarrow$

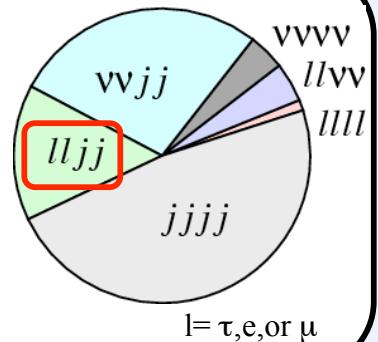
Outer contour: physically allowed region

Inner contour: 95% C.L. exclusion

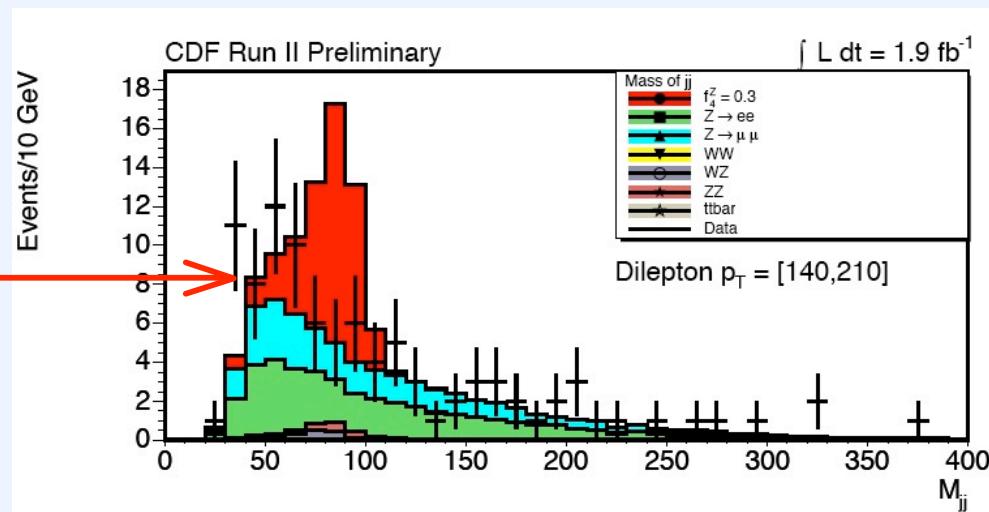
Crosshairs: 1-D exclusion limits



- CDF @  $1.9 \text{ fb}^{-1}$ :  $ZZ \rightarrow lljj$  channel
- Higher Branching ratio, large  $Z + \text{jets}$  background
- Signal from anomalous  $ZZZ/ZZ\gamma$  couplings expected at large  $P_T(Z)$
- Use dijet mass spectrum in high  $P_T(Z)$  regions to constrain potential contribution from anomalous couplings



Expected AC signal from  $f_4^Z = 0.3$  (LEP Limit)



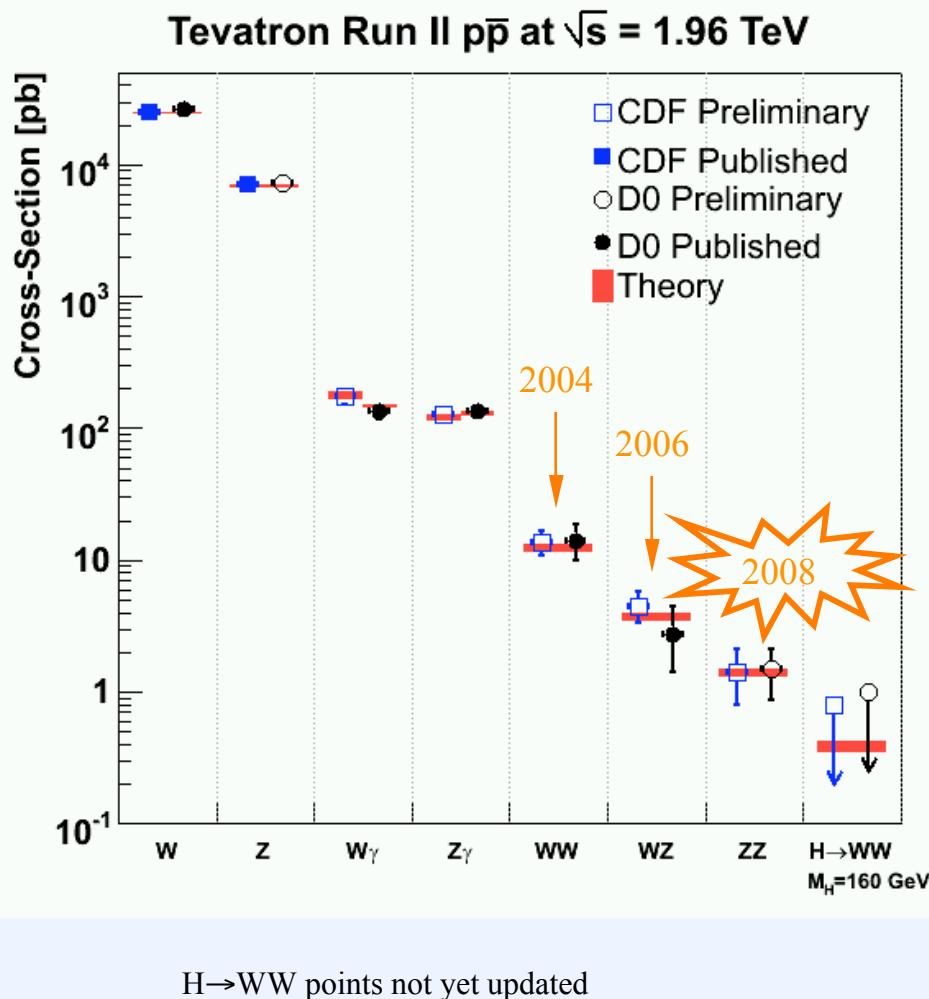
$\Lambda = 1.2 \text{ TeV}$

$-0.12 < f_4^Z < 0.12$
$-0.13 < f_5^Z < 0.12$
$-0.10 < f_4^\gamma < 0.10$
$-0.11 < f_5^\gamma < 0.11$

95% C.L. Limits



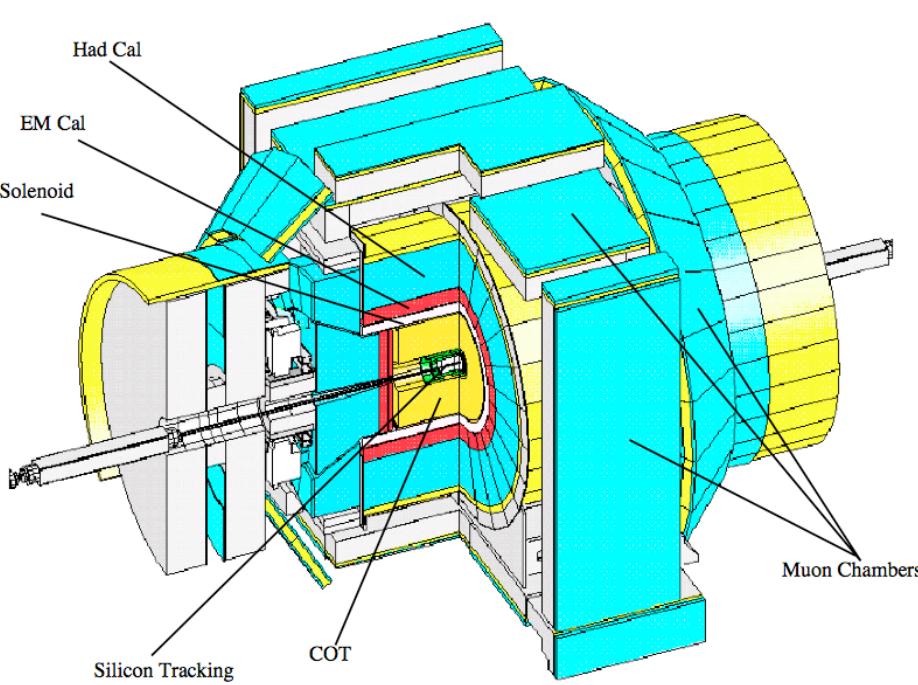
# Summary



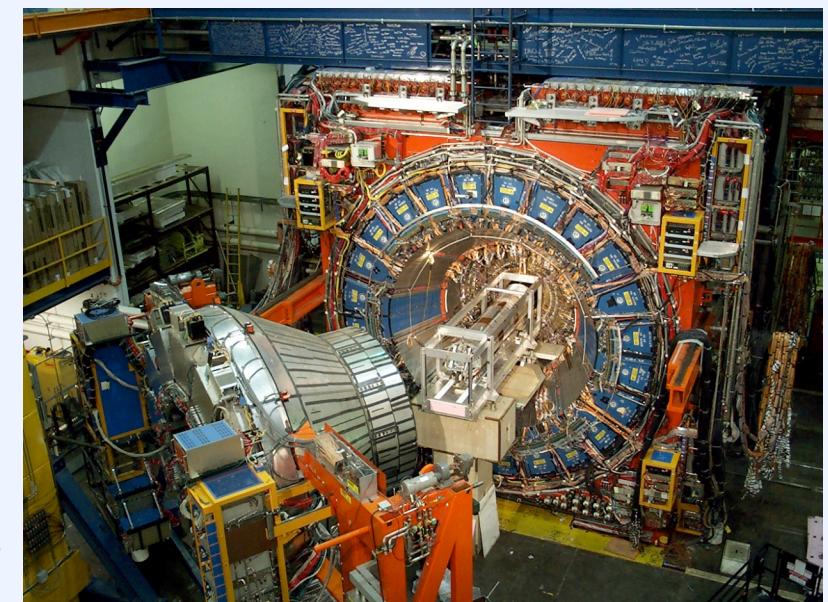
- Both CDF and D0 are measuring heavy diboson production and couplings with greater and greater precision
- ZZ production has been observed at the Tevatron!
- New limits set on anomalous coupling for ZZZ/ZZ $\gamma$  production
- Next up for the Tevatron: H $\rightarrow$ WW...

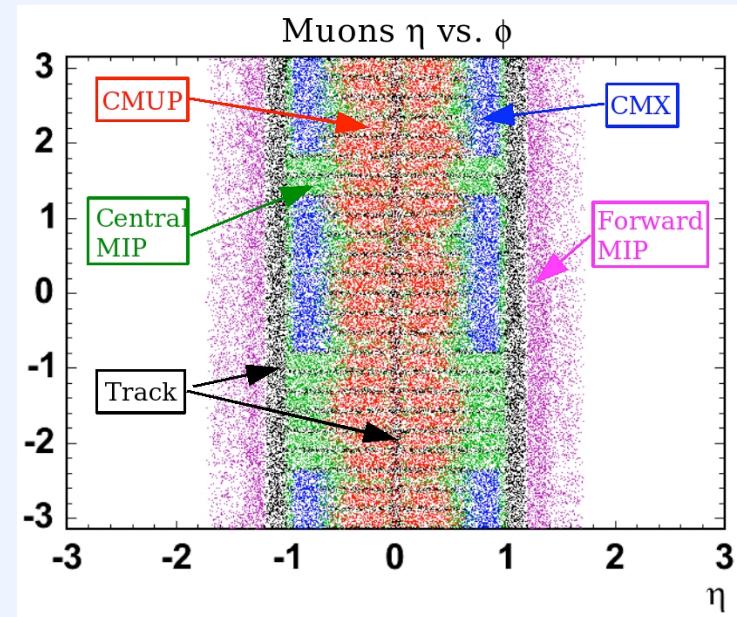
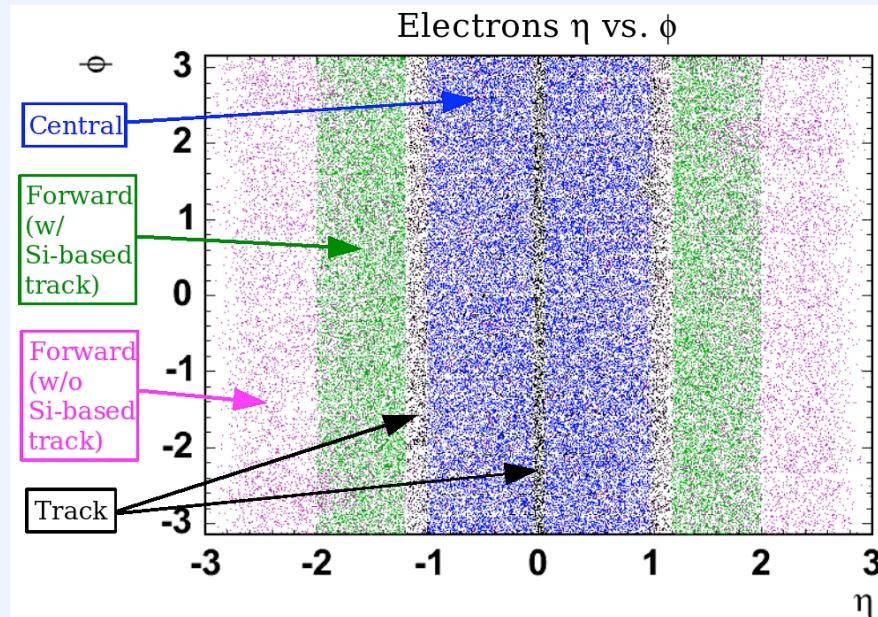


# Backup Slides



- Pb/Fe sampling calorimeter,  $|\eta| < 3.6$ 
  - Measures energy of electrons, photons and jets
  - Minimum ionizing particle energy for muons
- Muon Detectors,  $|\eta| < 1.5$ 
  - Wire chambers and scintillators identify muons

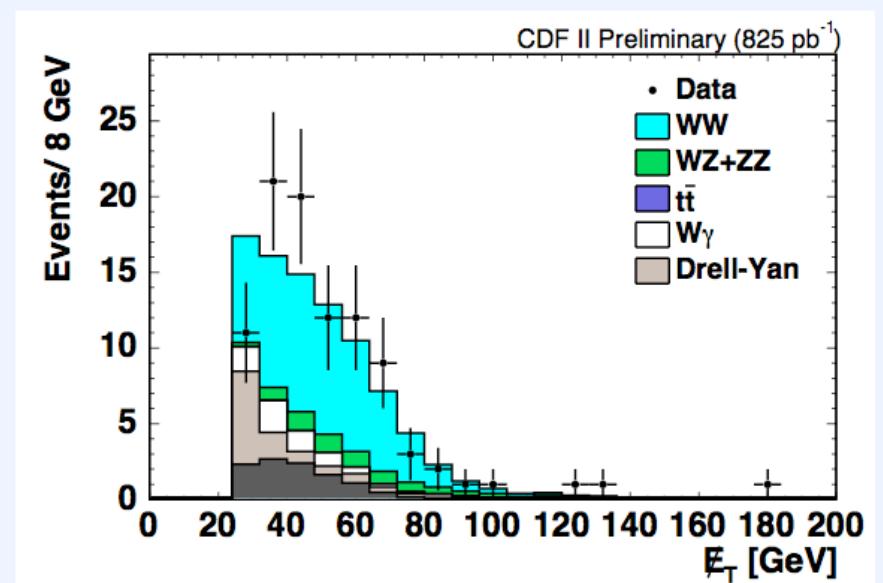




- Incorporate extended lepton identification to maximize acceptance
  - New forward electron candidates without track match
  - New forward muon candidates fiducial to calorimeter
  - New flavor-neutral leptons from unmatched tracks pointing to holes in detector coverage (electrons or muons)

- Update from CDF at  $\sim 825 \text{ pb}^{-1}$ 
  - Backgrounds: Z/ $\gamma^*$ , tt, WZ, ZZ, W $\gamma$  ( $\gamma$  fakes lepton), and W+jets (jet fakes lepton)

Selection: CDF @ 825 pb <sup>-1</sup>
2 isolated, opposite sign leptons (e or $\mu$ ), $P_T > 20 \text{ GeV}$
0 jets, $P_T > 15 \text{ GeV}$ , $ \eta  < 2.5$
Missing- $E_T$ (MET) $> 25 \text{ GeV}$
$\Delta\phi(\text{MET}, l) > 0.3$ (if MET $< 50 \text{ GeV}$ ) $\text{MET}/\sqrt{\sum E_T} > 3.0 \text{ GeV}^{1/2}$ (if $76 < M_{ll} < 106 \text{ GeV}$ )



Well-understood sample critical for H → WW!

- 95 candidates,  $37.8 \pm 4.8$  expected background events

$$\sigma(WW) = 13.6 \pm 2.3(\text{stat}) \pm 1.6(\text{syst}) \pm 1.2(\text{lum}) \text{ pb}$$

- Distinguish ZZ from WW with event-by-event probability density function

$$P(\vec{x}_{obs}) = \frac{1}{\langle \sigma \rangle} \int \frac{d\sigma^{LO}(\vec{y})}{d\vec{y}} \varepsilon(\vec{y}) G(\vec{x}_{obs}, \vec{y}) d\vec{y}$$

$\vec{x}_{obs}$  = observed leptons and MET

$\varepsilon(\vec{y})$  = total efficiency  $\times$  acceptance

$\vec{y}$  = True lepton four-vectors (with neutrinos)

$G(\vec{x}_{obs}, \vec{y})$  = resolution effects

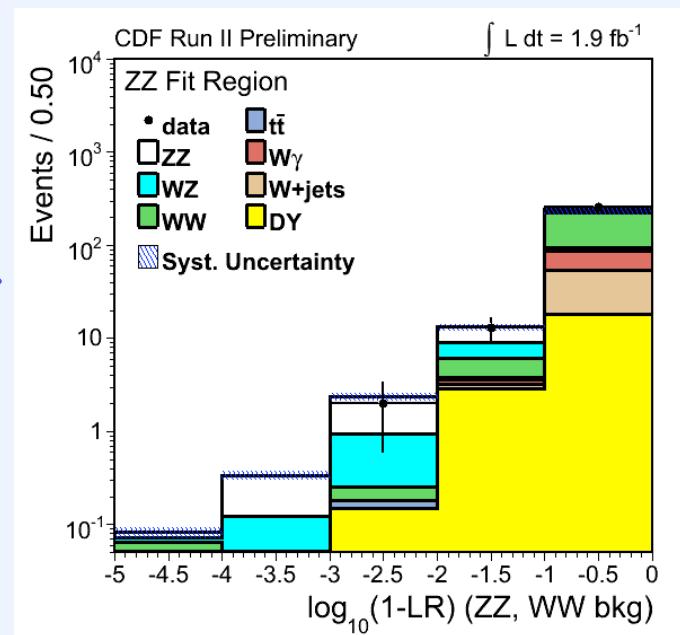
$\sigma$  = Leading order theoretical cross section

$$LR(\vec{x}_{obs}) = \frac{P_{ZZ}(\vec{x}_{obs})}{P_{ZZ}(\vec{x}_{obs}) + P_{WW}(\vec{x}_{obs})}$$

- Probability for background alone to describe data:

Observed Results: CDF @ 1.9 fb $^{-1}$

P-Value	0.12
Significance	1.2 $\sigma$



- Expected: probability to see  $2\sigma$  ( $5\sigma$ ) effect: 0.55 (0.06)